Ultrashort, high brightness beams at low charge from RF photoinjectors

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Outline

• Motivation and challenges for ultrashort electron bunches with low transverse emittance

• Ultralow emittance measurement techniques

• Velocity bunching at few MeV energies:
  – How short can we get?
  – How short can a deflecting cavity measure?

• Generation of ultralow emittance beams with sub-10 fs pulse length
Low Charge, high 5-D brightness beams

- Ultralow charge (<0.1 pC) beams with high 5D brightness ($\propto \frac{q}{\epsilon_x \epsilon_y \sigma_t}$) of interest for:
  - Ultrafast electron diffraction/microscopy: *single shot imaging, high res*
  - DLA: *few fs acceleration bucket, sub-micron aperture*

- Ultralow $\epsilon_x$ (few 10’s of nm) requires *ultrasmall source* (few 10’s of micron) with a Cu photocathode.

- Ultrashort $\sigma_t$ requires minimizing/cancelling RF and space charge induced emittance ($z$) in gun and buncher.

- Requires *measurement of microscopic beam sizes* ($x, y, t$).
Pegasus RF photoinjector

1) S-band Gun

2) Linac/Buncher

3) X-band Deflector (400 kV)

D. Alesini et al., PRSTAB 18, 092001 (2015)

N. Barov et al., PAC 2013

R. J. England et al., PAC 2005
Oblique Incidence laser illumination

- Utilize oblique (72 deg) incidence port and final focus lens to create small initial emittance.

175 mm lens

25 mm stage

UV on Virtual Cathode ~ 8 x 18 μm
Cu MTE @ 266 nm ~ 350 meV, or
7 nm x 15 nm therm. emittance

Set final focus position via space charge limit...

σ_{t,uv} \sim 100 \, fs

...or UV two-photon enhancement

(70 \, MV/m) \sin(25 \, \text{deg}) \rightarrow 160 \, \text{fC}
“pancake” space charge limit.

Sets bunch charge scale to 10s of fC.
Ultralow emittance measurement

- An in-vacuum microscope images a 20 micron thick YAG:Ce for high spatial resolution beam profiling.
  - Infinity corrected, coupled to CCD in air
  - Beam sizes of 3x3 micron observed
  - Emittances as low as 5 nm measured

On Crest

Velocity bunching

Penalty from velocity bunching: Increased energy spread and energy jitter (nearly maximum $d\gamma/d\phi$).
Velocity Bunching (no space charge)

- Neglecting space charge, sub-fs pulses emerge in simulation with short drive laser pulses (100 fs here)

- For sub-fs pulses, transverse dynamics matter! [M. de Loos et al., PRSTAB 9, 084201 (2006) ]
Velocity bunching (with space charge)

• Short laser pulses:
  – Space charge lengthening in gun and additional phase space curvature depends on initial beam size.
  – Few fs possible, sub-fs challenging without additional compensation.
• Ps-scale laser pulses relax the x-z crosstalk, but RF curvature remains
• Minimize or compensate rf emittance:
  – Minimize: Run gun at lower phase (lower $\epsilon_z$)
Deflecting Cavities and bunching beams

- What does a deflecting structure measure when $\sigma_t$ changes inside the cavity?
- First guess: $\langle \sigma_t \rangle \rightarrow$ poor resolution for bunching beams?
- In the case of a fully non-laminar focus, where head becomes tail, not true!

\[ \delta p_y = 0 \]
Deflecting Cavities and bunching beams

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Only residual head-tail momentum difference determined by the minimum $\sigma_t$

Aberration-free deflecting structures can measure longitudinal waist
Position of focus must be correct!
Deflecting Cavities and bunching beams

• What if waist does not occur in the center of the cavity?
• For small offsets, the deflector measures $\sigma_t$ at cavity center.
• Simulated measurement with Pegasus 9-cell deflector
  – scan position of longitudinal focus inside deflector (no space charge)

K. Floettmann 2014: For $\sigma_x \gg \sigma_z$, space charge does not necessarily add laminarity to longitudinal focus. *
• The above still holds in these cases.

* “Generation of sub-fs electron beams at few-MeV energies”, NIMA (2014)
Velocity bunching at Pegasus

- Recent experimental results (preliminary): Short laser pulse, ~100 fs
  - ~5 MeV, 20 fC full beam (no slit), quad focusing on final YAG:Ce screen

Scan linac phase through longitudinal beam minimum.

Fit deflector-off distribution to Guassian, subtract from fits to deflector-on.

\[
\sigma_t = \left( \frac{4 fs}{px} \right) \sqrt{\sigma_{y, on}^2 - \langle \sigma_{y, off} \rangle^2}
\]

~14 fs “off” width
Using 0.5 mm YAG: Ce.

Must improve PSF...
Velocity bunching at Pegasus

- Recent experimental results (preliminary): Short laser pulse, ~100 fs
  - ~5 MeV, 20 fC full beam (no slit), quad focusing on final YAG:Ce screen

Replace with 50 micron thick YAG—deflector-off now 7-8 fs.

→ 7 fs!
Velocity Bunching at Pegasus

- Long pulse: $\sigma_{t,uv} = 1.1 \text{ ps}$

- Broad core and long tail from large RF emittance.
- Smaller FWHM and suppressed tail, yielding Gaussian fit <10fs
Conclusions

• Utilized oblique UV illumination with final focus lens for small initial emittance

• Yields emittances on the scale of 10-20 nm, even downstream of bunching cavity

• Deflecting cavities aren’t inherently limited in their measurement of velocity bunched beams

• Direct measurement of sub-10 fs bunch lengths for 100 fs and 1 ps laser pulses on cathode

• Long. emittance reduction and deflecting resolution critical to achieve sub-fs
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